Star Forming Galaxies at $z \approx 6$ and Reionization

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Abstract

We have determined the abundance of i'-band drop-outs in the *HST*/ACS GOODS surveys and the Hubble Ultra Deep Field (UDF). The majority of these sources are likely to be $z \approx 6$ galaxies whose flux decrement between the F775W i'-band and F850LP z'-band arises from Lyman-alpha absorption. We have shown with Keck/DEIMOS and Gemini/GMOS spectroscopy that this technique does indeed select high redshift galaxies, and we discovered Lyman-α emission in the expected redshift range for about a third of the galaxies with $z'_{AB} < 25.6$ in the $150\,\mathrm{arcmin}^2$ of the GOODS-South field. The i-drop number counts in the GOODS-North field are consistent, so cosmic variance is possibly not the dominant uncertainty. The increased depth of UDF enables us to reach a $\sim 10\,\sigma$ limiting magnitude of $z'_{AB} = 28.5$ (equivalent to $1.5\,h_{70}^{-2}\,M_\odot\,\mathrm{yr}^{-1}$ at $z = 6.1$, or $0.1\,L^*_{UV}$ for the $z \approx 3$ U-drop population). The star formation rate at $z \approx 6$ was approximately $\times 6$ *less* than at $z \approx 3$. This declining comoving star formation rate ($0.005\,h_{70}\,M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$ at $z \approx 6$ at $L_{UV} > 0.1\,L^*$ for a Salpeter IMF) poses an interesting challenge for models which suggest that $L_{UV} > 0.1\,L^*$ star forming galaxies at $z \simeq 6$ reionized the universe. The short-fall in ionizing photons might be alleviated by galaxies fainter than our limit, or a radically different IMF. Alternatively, the bulk of reionization might have occurred at $z \gg 6$. We have recently discovered evidence of an early epoch of star formation in some of the i'-drops at $z \approx 6$. *Spitzer* images with IRAC at $3.6 - 4.5\,\mu$m show evidence of the age-sensitive Balmer/4000 Å, dominated by stars older than 100 Myr (and most probably 400 Myr old). This pushes the formation epoch for these galaxies to $z_{\mathrm{form}} = 7.5 - 13.5$. There are at least some galaxies already assembled with stellar masses $\approx 3 \times 10^{10}\,M_\odot$ (equivalent to $0.2\,M^*$ today) within the first billion years. The early formation of such systems may have played a key role in reionizing the Universe at $z \sim 10$.

Preprint submitted to New Astronomy *5 February 2008*

1 Introduction

There has been enormous progress over the past decade in discovering galaxies and QSOs at increasingly high redshifts. We are now probing far enough back in time that the Universe at these early epochs was fundamentally different from its predominantly ionized state today. Observations of $z > 6.2$ QSOs (Becker et al. 2001, Fan et al. 2002) show near-complete absorption of flux at wavelengths short-ward of Lyman-α (Gunn & Peterson 1965), indicating that the Universe is optically thick to this line, and that the neutral fraction of hydrogen is much greater than at lower redshifts. Initial cosmic microwave background results from the *WMAP* satellite indicated that the Universe was completely neutral at redshifts of $z \sim 10$ (Kogut et al. 2003). There is an ongoing debate as to what reionized the Universe at $z > 6$: is it AGN or ionizing photons (produced in hot, massive, short-lived stars) escaping from star forming galaxies? Along with the escape fraction for these ionizing photons, it is crucial to know the global star formation rate at this epoch.

Here we detail our work in identifying star-forming galaxies within the first billion years of the Big Bang through deep imaging with the *Hubble Space telescope (HST)*. Our selection method is based on the Lyman break technique, and we have shown this is effective in isolating $z \approx 6$ by obtaining spectroscopic confirmation with the 10-m Keck telescopes. Our analysis of the *Hubble Ultra Deep Field* (the deepest images ever obtained) enables us to explore the faint end of the luminosity function (the bulk of galaxies with low star formation rates). Our discovery of this i'-drop galaxy population is used to infer the global star formation rate density at this epoch ($z \approx 6$). We consider the implications for reionization of the UV flux from these galaxies. We also use infrared data from the *Spitzer Space Telescope* to determine the spectral energy distributions (SEDs) of our i'-drops, and constrain the previous star formation histories of these sources.

Throughout we adopt the standard "concordance" cosmology of $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and use $h_{70} = H_0/70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. All magnitudes are on the *AB* system.

2 The Lyman-Break Technique at $z \approx 6$

In order to select $z \approx 6$ galaxies, we use the "Lyman break technique" pioneered at $z \sim 3$ using ground-based telescopes by Steidel and co-workers (Steidel, Pettini & Hamilton 1995; Steidel et al. 1996) and using *HST* by Madau et al. (1996). At $z \approx 6$, we can efficiently use only two filters, above (z'-band 9000Å) and below (i'-band 8000Å) the continuum break at Lyman-α

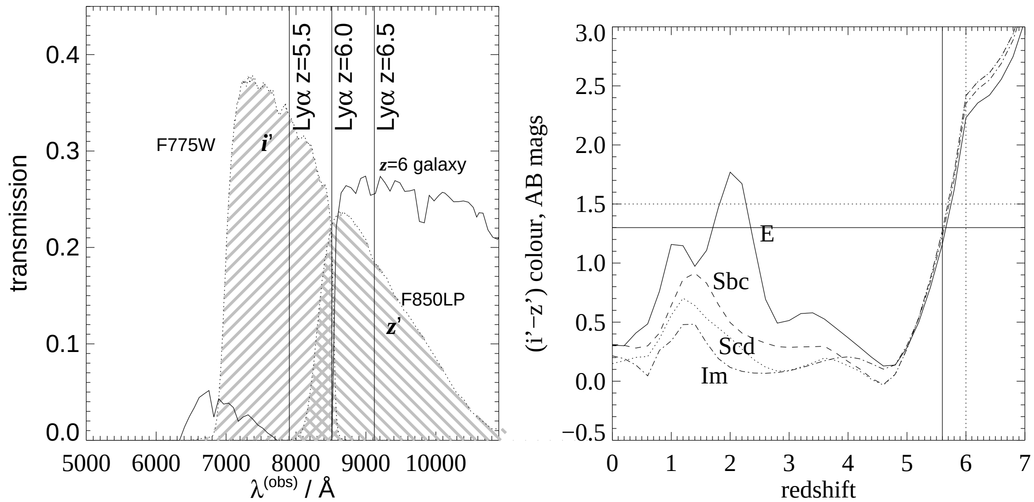

Fig. 1. **Left:** The ACS-i' and -z' bandpasses overplotted on the spectrum of a generic $z = 6$ galaxy (solid line), illustrating the utility of our two-filter technique for locating $z \approx 6$ sources. **Right:** Model colour-redshift tracks for galaxies with non-evolving stellar populations (from the template spectra of Coleman, Wu & Weedman 1980, ApJS 43, 393). The contaminating 'hump' in the $(i' - z')$ colour at $z \approx 1 - 2$ arises when the Balmer break and/or the 4000 Å break redshifts beyond the i'-filter.

line ($\lambda = (1 + \mathrm{z}) \times 1216$ Å) since the integrated optical depth of the Lyman-α forest is $\gg 1$ (see Figure 1) and there is essentially no flux at shorter wavelengths. The key issue is to work at a sufficiently-high signal-to-noise ratio that Lyman break "drop-out" galaxies can be safely identified through detection in a single redder band (i.e., z'-band). This approach has been demonstrated to be effective by the SDSS collaboration in the detection of $z \approx 6$ QSOs using the i'- and z'-bands alone (Fan et al. 2002), using wide-area but shallow ground-based imaging (sensitive to bright but rare quasars). Our group has analysed deep imaging from the Advanced Camera for Surveys (ACS) on *HST* with the same sharp-sided SDSS F775W (i') and F850LP (z') filters to locate the"i-drops" which are candidate $z \approx 6$ galaxies (fainter but more numerous than the QSOs). In Figures 1 & 2 we illustrate how a colour cut of $(i' - z')_{AB} > 1.3$ can be effective in selecting sources with $z > 5.6$.

We have analysed the ACS images from the *HST* Treasury "Great Observatory Origins Deep Survey" (GOODS; Giavalisco & Dickinson 2003) to discover this i'-drop population of $z \approx 6$ galaxies. In Stanway, Bunker & McMahon (2003) we searched 150 arcmin^2 of the GOODS-South field (the *Chandra* Deep Field-South) to select $(i' - z')_{AB} > 1.5$ objects, of which six were probable $z > 5.7$ galaxies brighter than $z_{AB} < 25.6$. Subsequent papers by the GOODS team (Dickinson *et al.* 2004; Giavalisco *et al.* 2004) reproduced many of these i'-drop candidates. To address potential cosmic variance issues, we performed a similar analysis in the GOODS-North field, which yielded a consistent estimate of the surface density of $z \simeq 6$ star forming sources (Stanway et al. 2004b).

2.1 Spectroscopic Confirmation of $z \approx 6$ Galaxies

The effectiveness of the Lyman-break technique has been demonstrated at lower redshifts through spectroscopic confirmation of hundreds of U-band dropouts at $z \approx 3$ and B-band drop-outs at $z \approx 4$. However, it is important to demonstrate that the i'-drop selection is similarly isolating galaxies at $z \approx 6$, if we are to use the surface density of i'-drops to draw global inferences about galaxies within the first billion years. A known possible contaminant is the Extremely Red Object (ERO) population of evolved galaxies at $z \approx 1-2$ which can produce large $(i' - z')$ colours: deep near-infrared imaging (e.g., from the *HST*/NICMOS survey of the UDF) should identify EROs, and we consider this possible contamination Stanway, McMahon & Bunker (2005). Low-mass Galactic stars (M/L/T dwarfs) are another interloper population.

We have obtained deep spectroscopy with Keck/DEIMOS of several of the brightest i'-drops identified by Stanway, Bunker & McMahon (2003) in GOODS-South; in the case of SBM03#3 ($z' = 25.6$) and , an i'-drop in the Chandra Deep Field South photometrically-selected from HST/ACS images to lie at $z \approx 6$.

For two of these objects, we discovered single emission lines (Fig. 3) at 8245 Å & 8305 Å, consistent with Lyman-α emission from galaxies at $z = 5.78$ (SBM03#3, Bunker et al. 2003) and $z = 5.83$ (SBM03#1, Stanway et al. 2004a). The spectrally-resolved profiles of the emission lines are asymmetric (as high-z Lyman-α tends to be) with a P-Cygni-like profile and a sharp cut-off on the blue wing (Fig. 2). The line fluxes are $\approx 2 \times 10^{-17}\,\mathrm{ergs\,cm^{-1}\,s^{-1}}$. The equivalent widths are $W_{\mathrm{rest}} = 20 - 30$ Å using the z'-band photometry from HST/ACS, which is within the range seen in high-z star-forming galaxies at $z \sim 3-4$. The velocity widths of the Lyman-α are comparatively narrow ($v_{\mathrm{FWHM}} = 300\,\mathrm{km\,s^{-1}}$) and we do not detect the high-ionization line N v λ 12140 Å, which strongly support the view that this line emission is powered by star formation rather than an AGN. Our spectroscopic redshifts for these objects confirms the validity of the i'-drop selection technique to select star-forming galaxies at $z \approx 6$. Subsequently, a programme of spectroscopy with GMOS "nod & shuffle" on Gemini (GLARE, Stanway et al. 2004b) has confirmed more galaxies in GOODS-South. Slitless spectroscopy of the UDF with *HST*/ACS (GRAPES, Malhotra et al. 2005) has also confirmed the spectral breaks of the i'-drop galaxies, although the spectral resolution of $R \approx 70$ is insufficient to see the Lyman-α emission lines.

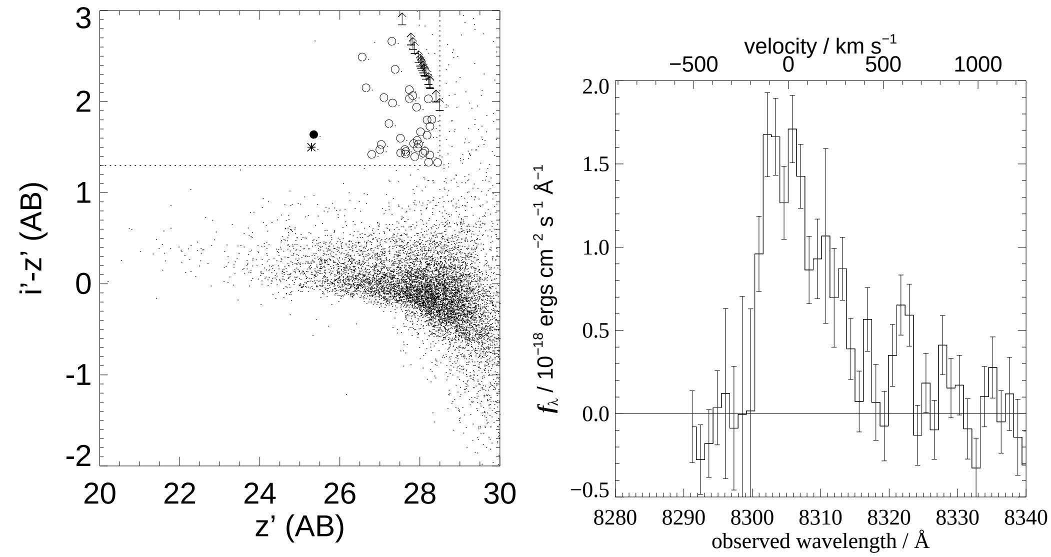

Fig. 2. **Left:** Colour-magnitude diagram for the UDF data with the limit $z'_{AB} < 28.5$ and $(i' - z')_{AB} = 1.3$ colour cut shown (dashed lines). Such a catalogue could be contaminated by cool stars, EROs and wrongly identified extended objects and diffraction spikes but nonetheless provides a secure upper limit to the abundance of z≈ 6 star forming galaxies. Circles and arrows (lower limits) indicate our i'-drop candidate $z \approx 6$ galaxies. The asterisk is the only unresolved i'-drop in our UDF sample, a probable star. The solid circle is the brightest i'-drop in the UDF, the spectroscopically-confirmed galaxy SBM03#1 at $z = 5.83$, with our discovery spectrum from Keck/DEIMOS shown (**right**, Stanway et al. 2004b.

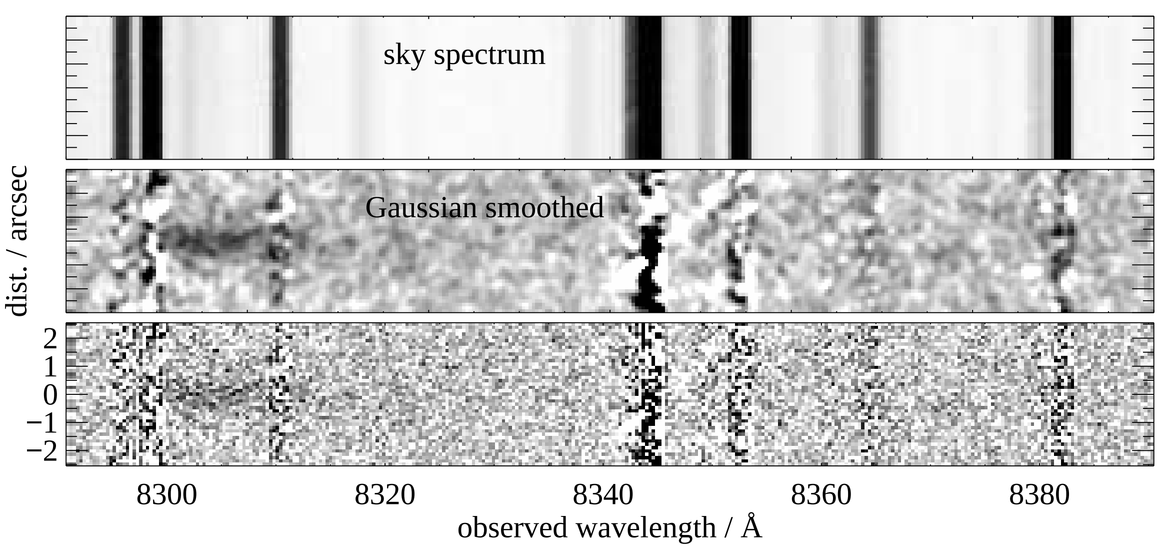

Fig. 3. Our 2D Keck/DEIMOS spectrum confirming the brightest i'-drop in the UDF is indeed a $z \approx 6$ galaxy: prominent Lyman-α emission is seen at $z = 5.83$ (from Stanway et al. 2004b). There has been independent spectroscopic confirmation by Dickinson et al. (2004).

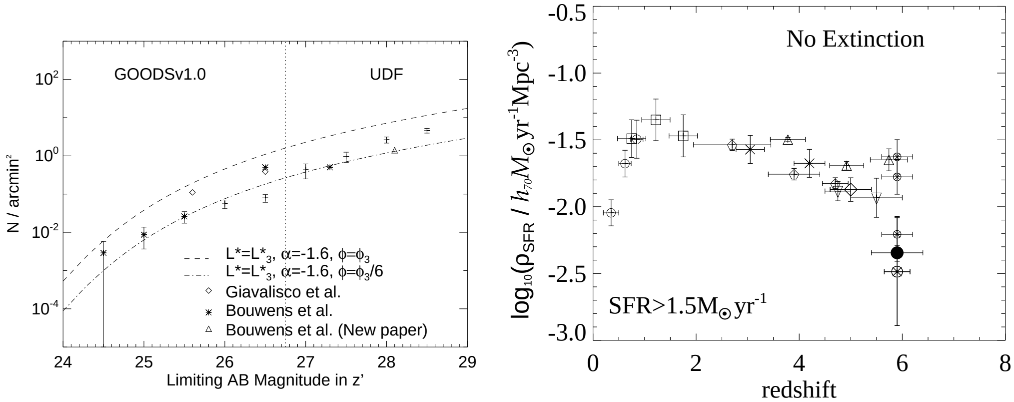

Fig. 4. **Left:** Cumulative source counts per arcmin^2 of i'-dropouts as a function of z'-band magnitude. The new UDF data (over an area of 11 arcmin^2 for $28.5 \geq z'_{AB} \geq 27.0$) is compared with our $z'_{AB} \leq 25.6$ single epoch GOODSv0.5 ACS/WFC imaging over 300 arcmin^2 (Stanway, Bunker & McMahon 2003; Stanway et al. 2004), and combined 5 epoch GOODSv1.0 images to $z'_{AB} < 27.0$ (Stanway 2004, PhD. thesis, Cambridge University). Also plotted are the surface densities of i'-drops from Giavalisco et al. (2004) Bouwens et al. (2003, 2004)
Right: An updated version of the 'Madau-Lilly' diagram (Madau et al. 1996; Lilly et al. 1996) illustrating the evolution of the comoving volume-averaged star formation rate. Our work from the UDF data is plotted a solid symbol. Other determinations have been recalculated for our cosmology and limiting UV luminosity of $1.5\,h_{70}^{-2}\,M_{\odot}\,\mathrm{yr}^{-1}$ at $z = 6.1$ (equivalent to $0.1\,L_3^*$ at $z \approx 3$ from Steidel et al. 1999), assuming a slope of $\alpha = -1.6$ for $z > 2$ and $\alpha = -1.3$ for $z < 2$. Data from the CFRS survey of Lilly et al. (1996) are shown as open circles; data from Connolly et al. (1997) are squares; and the Lyman break galaxy work of Steidel et al. (1999) is plotted as crosses, of Fontana et al. (2002) as inverted triangles and that by Iwata et al. (2003) as an open diamond. Pentagons are from Bouwens, Broadhurst & Illingworth (2003), upright triangles are the GOODS i'-drop results from Giavalisco et al. (2004). The three ACS estimates of Bouwens et al. (2003) are shown by small crossed circles and indicate three different completeness corrections for one sample of objects – the larger symbol is the recent re-determination using a new catalogue by this group from a deeper dataset (the UDF flanking fields – Bouwens et al. 2004).

3 The star formation rate density at $z \approx 6$

We base our measurement of the star formation rate on the intensity of the rest-frame UV continuum emission, redshifted into the z'-band at $z \approx 6$; this is dominated by the light from the most massive stars ($M > 10\,M_{\odot}$ which are the hottest and bluest stars), which are the shortest lived, and hence a tracer of the instantaneous star formation rate. To go from the number of massive stars formed to the total star formation rate requires an assumption about the stellar initial mass function (IMF). In the absence of dust obscuration, the relation between the flux density in the rest-UV around ≈ 1500 Å and the star formation rate (SFR in $M_{\odot}\,\mathrm{yr}^{-1}$) is given by $L_{\mathrm{UV}} = 8 \times 10^{27}\mathrm{SFR}\,\mathrm{ergs}\,\mathrm{s}^{-1}\,\mathrm{Hz}^{-1}$

from Madau, Pozzetti & Dickinson (1998) for a Salpeter (1955) IMF with $0.1\,M_\odot < M^* < 125\,M_\odot$. Our relatively bright magnitude cut of $z'_{AB} < 25.6$ for the GOODSv0.5 data (Stanway, Bunker & McMahon 2003; Stanway et al. 2004a) corresponds to an unobscured star formation rate of $15\,h_{70}^{-2}\,M_\odot\,\mathrm{yr}^{-1}$ at $z = 5.9$ (the luminosity-weighted average redshift), equivalent to L^*_{UV} for the U-band dropout population at $z \approx 3$.

We recover the $z \approx 6$ rest-frame UV luminosity function from the observed number counts of i'-drops to faint magnitudes in the UDF. Although our colour cut selects galaxies with redshifts in the range $5.6 < z < 7.0$, an increasing fraction of the z'-band flux is attenuated by the redshifted Lyman-α forest. At higher redshifts we probe increasingly shortward of $\lambda_{\mathrm{rest}} = 1500\,\text{Å}$ (where the luminosity function is calculated) so the k-corrections become significant beyond $z \approx 6.5$.

We now compare the comoving star formation rate deduced for $z \approx 6$ galaxies based on our candidate i'-dropout source counts with predictions based on a range of rest-frame UV luminosity functions. For convenience we assume that there is no evolution over the sampled redshift range, $5.6 < z < 6.5$, spanned by our i'-drop selection (equivalent to a range between $0.8 - 1.0\,h_{70}^{-1}$ Gyr after the Big Bang). We take as a starting point the luminosity function for the well-studied Lyman-break U-dropout population, reported in Steidel et al. (1999), which has a characteristic rest-UV luminosity $L^*_3 = 15\,h_{70}^{-2}\,M_\odot\,\mathrm{yr}^{-1}$ and a characteristic comoving number density at $z \approx 3$ is $\Phi^*_3 = 0.0014\,h_{70}^3\,\mathrm{Mpc}^{-3}\,\mathrm{mag}^{-1}$ in our cosmology. The faint end slope of the Schechter function at $z \approx 3$ is relatively steep ($\alpha = -1.6$) compared with $\alpha = -1.0$ to -1.3 for lower-redshift galaxy samples (e.g., Blanton et al. 2003).

A tantalizing result from our work so far is that at $z \sim 6$ there are far fewer UV-luminous star forming galaxies than would have been predicted if there was no evolution, based on a comparison to the well-studied $z \sim 3-4$ Lyman break population (Steidel et al. 1999). In fact, the volume averaged (comoving) star formation rate in galaxies with $> 15\,h_{70}^{-2}\,M_\odot\,\mathrm{yr}^{-1}$ is $\approx 6\times$ *less* at $z \approx 6$ than at $z \approx 3$. So it would appear that at this crucial epoch, where abundant sources of UV photons are needed to reionize the Universe, there is in fact a deficit of luminous star forming galaxies. We have conclusively shown that the bright end of luminosity function has evolved greatly from $z \sim 6$ to $z \sim 3$. Other groups have claimed less dramatic evolution or even no evolution in the total volume-averaged star formation rate, based on the same fields (Giavalisco et al. 2004; Dickinson et al. 2004) and similar *HST*/ACS data sets (Bouwens et al. 2003; Yan, Windhorst & Cohen 2003), but these groups work closer to the detection limit of the images and introduce large completeness corrections for the faint source counts. To do a complete inventory of the UV light from star formation we must address the contribution of low-luminosity star-forming galaxies to the ionizing flux. The public availability of the Hubble

Ultra Deep Field (UDF; Beckwith, Somerville & Stiavelli) can address this puzzle by pushing down the luminosity function at $z \approx 6$ to well below the equivalent of L^* for the $z \approx 3$ population.

4 The Hubble Ultra Deep Field

The Hubble Ultra Deep Field (UDF) was a Cycle 12 STScI Director's Discretionary Time programme executed over September 2003 – January 200, comprising 400 orbits in 4 broad-band filters (including F775W i'-band for 144 orbits; F850LP z'-band for 144 orbits). The UDF lies within the Chandra Deep Field South (CDF-S). As the UDF represents the deepest set of images yet taken, significantly deeper than the I-band exposures of the Hubble Deep Fields (Williams et al. 1996), and adds the longer-wavelength z'-band, it is uniquely suited to the goals of our program.

We performed the first analysis of i'-drops in the UDF (Bunker et al. 2004), presenting details of 54 candidate star forming galaxies at $z \approx 6$ in a preprint the day after the release of the UDF data. Our analysis was subsequently independently repeated by Yan & Windhorst (2004), with agreement at the 98% level (see Bunker & Stanway 2004 for a comparison). We take our magnitude limit as $z'_{AB} < 28.5$ (a $10\,\sigma$ cut).We measure a star formation density of $0.005\,h_{70}\,M_{\odot}\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$ at $z \approx 6$ from galaxies in the UDF with SFRs $> 1.5\,h_{70}^{-2}\,M_{\odot}\,\mathrm{yr}^{-1}$ (equivalent to $0.1\,L^*_{UV}$ at $z \approx 3$).

At the relatively bright cut of $z'_{AB} < 25.6$ used in Stanway, Bunker & McMahon (2003) from the GOODSv0.5 survey, the UDF data is 98% complete for sources as extended as $r_h = 0.5$ arcsec. Interestingly, we detect no extended (low surface brightness) i'-drops to this magnitude limit in addition to the targetted i'-drop SBM03#1 in the deeper UDF data. This supports our assertion that the i'-drop population is predominantly compact and there cannot be a large completeness correction arising from extended objects (c.f. Lanzetta et al. 2002). The ACS imaging is of course picking out HII star forming regions, and these UV-bright knots of star formation are typically compact (< 1 kpc, < 0.2 arcsec at $z \approx 6$) even within large galaxies at low redshift.

It is interesting that the level of stellar contamination in the UDF i'-drops is only 2%, compared with about one in three at the bright end ($z'_{AB} < 25.6$; Stanway, Bunker & McMahon 2003; Stanway et al. 2004). This may be because we are seeing through the Galactic disk at these faint limiting magnitudes to a regime where there are no stars (see also Pirzkal et al. 2005).

5 Implications for Reionization

We compare our i'-drop luminosity function with the work of Madau, Haardt & Rees (1999) for the density of star formation. We have updated their equation 27 for the more recent concordance cosmology estimate of the baryon density of Spergel et al. (2003), and for the predicted mean redshift of our sample ($z = 6.0$):

$$\dot{\rho}_{\rm SFR} \approx \frac{0.026\, M_\odot\, {\rm yr}^{-1}\, {\rm Mpc}^{-3}}{f_{\rm esc}} \left(\frac{1+z}{7}\right)^3 \left(\frac{\Omega_b\, h_{70}^2}{0.0457}\right)^2 \left(\frac{C}{30}\right) \tag{1}$$

This relation is based on the same Salpeter Initial Mass Function as we have used in deriving our volume-averaged star formation rate. C is the concentration factor of neutral hydrogen, $C = \langle\rho_{\rm HI}^2\rangle\, \langle\rho_{\rm HI}\rangle^{-2}$. Simulations suggest $C \approx 30$ (Gnedin & Ostriker 1997). The escape fraction of ionizing photons ($f_{\rm esc}$) for high-redshift galaxies is highly uncertain (e.g., Steidel, Pettini & Adelberger 2001), but even if we take $f_{\rm esc} = 1$ (no absorption by H I) this estimate of the star formation density required is a factor of ≈ 5 higher than our measured star formation density of $0.005\, h_{70}\, M_\odot\, {\rm yr}^{-1}\, {\rm Mpc}^{-3}$ at $z \approx 6$ from galaxies in the UDF with SFRs$>$ $1.5\, h_{70}^{-2}\, M_\odot\, {\rm yr}^{-1}$. For faint end slopes of $\alpha\ -1.8 \rightarrow -1.3$ galaxies with $L > 0.1\, L^*$ account for $32-80\%$ of the total luminosity, so would fall short of the required density of Lyman continuum photons required to reionize the Universe. If the faint-end slope is as steep as $\alpha \approx -1.9$ then there would just be enough UV Lyman continuum photons generated in star forming galaxies at $z \approx 6$ (assuming a Salpeter IMF), but the required escape fraction for complete reionization would still have to be implausibly high ($f_{esc} \approx 1$, whereas all high-z measurements to date indicate $f_{esc} \ll 0.5$: Fernánadez-Soto, Lanzetta & Chen 2003; Steidel, Adelberger & Pettini 2001).

AGN are also under-abundant at these epochs (e.g., Dijkestra, Haiman & Loeb 2004). If star forming galaxies at redshifts close to $z = 6$ were responsible for the bulk of reionization, then a very different initial mass function would be required, or the calculations of the clumping factor of neutral gas would have to be significantly over-estimated (see also Stiavelli, Fall & Panagia 2004). Alternatively another low-luminosity population (e.g., forming globular clusters; Ricotti 2002) could be invoked to provide some of the shortfall in ionizing photons. It is also plausible that the bulk of reionization occurred at redshifts well beyond $z = 6$: the WMAP polarization data indicate $z_{reion} > 10$ (Kogut et al. 2003), and it is possible that the Gunn-Peterson troughs seen in $z > 6.2$ QSOs (Becker et al. 2001; Fan et al. 2002) mark the very last period of a neutral IGM.

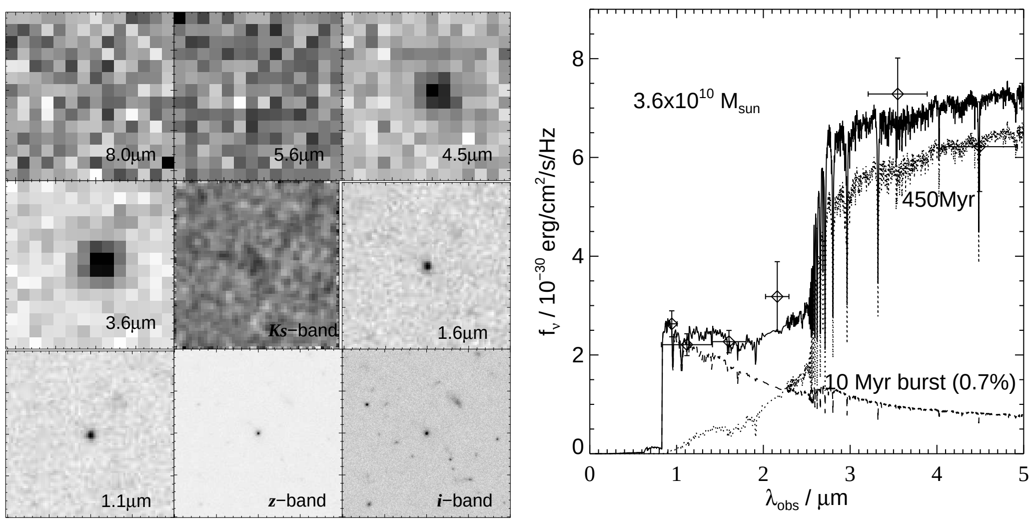

Fig. 5. **Left:** The *Spitzer* IRAC and *HST* ACS & NICMOS images of the $z = 5.83$ galaxy, SBM03#1. **Right:** the *Spitzer* and *HST* wavebands straddle the age-sensitive Balmer/4000 Å break, and reveal an underlying old (~ 400 Myr) population which dominates the stellar mass, $\sim 3 \times 10^{10}\, M_{\odot}$ (Eyles et al. 2005).

We have recently discovered evidence of an early epoch of star formation (Eyles et al. 2005). Some of the spectroscopically-confirmed i'-drops at $z \approx 6$ show evidence of another spectral break in the near-infrared (comparing *Spitzer* images with IRAC at $3.6 - 4.5\,\mu$m with *HST* NICMOS & ACS images at $0.8 - 1.6\,\mu$m). This age-sensitive Balmer/4000 Å break indicates the IR light is dominated by stars older than 100 Myr (and most probably 400 Myr old). This pushes the formation epoch for these galaxies to $z_{\rm form} = 7.5 - 13.5$. Our recent results also indicate that there were at least some galaxies already assembled with stellar masses $\approx 3 \times 10^{10}\, M_{\odot}$ (equivalent to $0.2\, M^*$ today) within the first billion years. The early formation of such systems may have played a key role in reionizing the Universe at $z \sim 10$.

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